Institute of Paper Science and Technology
Atlanta, Georgia

IPST TECHNICAL PAPER SERIES

NUMBER 441

SPRAYING CHARACTERISTICS OF COMMERCIAL BLACK LIQUOR NOZZLES

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MAY 1992

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Submitted to
International Chemical Recovery Conference
Seattle, WA
June 7–11, 1992

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Abstract

Black liquor at typical nozzle conditions has been sprayed through standard splashplate, V-jet, and swirl cone nozzles using an enclosed spray chamber. Flow rate/pressure drop characteristics were measured as a function of temperature and solids concentration. Videos of the resulting liquor sprays were subjected to image analysis, and droplet size distributions were determined. Mass fraction as a function of diameter follows a square root-normal distribution law. Median diameters have been correlated using statistically significant dimensionless groups. Implications for nozzle operating conditions on recovery furnace performance are discussed.

INTRODUCTION

Black liquor is sprayed into a recovery boiler through a pressure nozzle, after which the droplets that are formed go through the sequential processes of drying, pyrolysis and gasification, combustion, reduction, and smelt coalescence. The rates at which these physical and chemical processes occur are highly dependent upon the size and size distribution of the droplets formed from the spray. The smaller the droplet, the greater the surface area per unit mass of liquor and, hence, the greater the rates of heat and mass transfer. While this is highly desirable for capacity reasons, it is counterbalanced by higher entrainment and carryover, a characteristic of small particles in an upward flowing turbulent gas stream. The inevitable result is accelerated fouling of relatively cool boiler tubes and more rapid pluggage of the heat recovery section.

For black liquor throughput to be increased in recovery-boiler-limited mills, control of not only droplet size, but also the width of the size distribution must be improved. Existing recovery boiler nozzles have been designed with two primary objectives -- deliver production rates of liquor in a drop size range which gives acceptable combustion and reduction efficiencies and deliver the liquor reliably with minimal nozzle or boiler pluggage. Any improvements which provide incremental capacity, while maintaining high combustion and reduction efficiencies, will require better control of the size distribution.

Whether or not a narrower distribution should be the goal is still an open question. Too narrow a size distribution might not allow for a proper balance between suspension burning and burning on the char bed. Nonetheless, it seems likely that to raise capacity without increasing carryover will require a droplet distribution with a smaller fraction of the finer sizes.

The work reported here presents results of a study in which actual mill black liquors were sprayed through commercially available black liquor nozzles. Performance characteristics have been determined, including flow rate/pressure drop correlations, droplet size and size distribution, and correlation of the resultant mass-median diameters in terms of physical and operating parameters, as well as combinations of certain dimensionless groups.

The performance of spray nozzles for kraft black liquor has been the subject of several recent investigations (1-5). Although research is incomplete, some information is available about the performance of the three basic commercial types of black liquor nozzles: the splashplate, the swirl cone, and the U- or V-jet. Data have been reported on the flow and pressure drop characteristics and droplet size distributions, along with treatments of the mechanism of droplet formation from sprays. Also addressed is nozzle stability with respect to flashing ahead of the nozzle.

Bennington and Kerekes (3) were the first to report on the size and size distribution of droplets from black liquor nozzles. They used small, commercially available, grooved-core nozzles similar in operation to the swirl cone nozzles used currently for firing black liquor. The orifice size for their nozzles was only 0.7mm in diameter, about one-twentieth the size of a standard commercial nozzle. Not too surprisingly, the droplet sizes from the experimental nozzles (about 0.3mm) were about one-tenth those from typical black liquor nozzles. Data were reported for a 65% glycerol/water solution at room temperature and for 55% solids black liquor at 120°C. The viscosity of both these fluids was 0.015 kg/m/s (15 cP), which is somewhat lower than typical black liquor firing conditions. A high nozzle pressure ($1.38 \times 10^6 N/m^2$, 200 psi), along with the small nozzle size and relatively low liquor viscosity, led to the small droplet sizes reported. Results of their tests showed that black liquor appeared to give a much broader size distribution than glycerol/water; however, when plotted as a function of the diameter divided by the mass-median diameter, the data from the two fluids are nearly identical. The broader size distribution for black liquor was a result of its larger mass-median diameter. It is important to note that, if the operating conditions for the two fluids were manipulated to produce the same mass-median droplet size, then the size distributions for both would be identical. The size distribution about the mean is not a function of the fluid properties or operating parameters, but of the mechanism for sheet breakup. The basic characteristic of this mechanism is that it is random and disordered, and this results in a characteristic size distribution.

Bennington and Kerekes correlated their data for glycerol/water sprays based on the Sauter mean diameter, which is the fictitious spherical droplet having the same surface-to-volume ratio as the distribution as a whole.

$$\frac{D_{sm}}{D_n} = 1.6\,(We\ Re)^{-0.18} \qquad (1)$$

where:

D_{sm} = Sauter mean diameter, mm
D_n = nozzle diameter, mm
We = Weber number ($D_n V_n^2\ \rho/\sigma$)
Re = Reynolds number ($D_n V_n\ \rho/\mu$)
V_n = nozzle velocity
ρ = liquor density
σ = surface tension
μ = viscosity

Eq (1) was reported to underpredict the droplet size data for black liquor sprays by a factor of two. The initial black liquor viscosity was the same as that for glycerol/water, but the researchers speculated that the cause of the difference was a constantly increasing liquor viscosity as the initially hot sheet dried, cooled, and broke up into droplets.

The effect of temperature on black liquor droplet size showed diameter to decrease smoothly as liquor temperature was increased past its boiling point. There were not enough data to make any conclusions on the effect of flashing on liquor droplet size, although there is some evidence in the literature (6) that claims a few degrees change in liquor temperature can change a coarse spray into a fine mist.

In a separate study by Spielbauer, et al. (4), typical black liquor nozzles and other commercially available nozzles were evaluated. Included were a swirl cone, a splashplate, and a hollow cone nozzle. As with the previous data, Spielbauer's data have been plotted as a function of the diameter divided by the mass-median diameter. All the curves overlap substantially, indicating that the size distribution for each nozzle is very similar.

Once liquor droplets are formed, they are subject to stresses associated with aerodynamic shear as they move through the surrounding gas. Droplet disintegration may occur, depending on the balance of forces due to lift and drag and the resistance to breakup due to surface tension and viscosity. Stockel (5) reported on black liquor droplet formation from single jets. He observed the formation of satellite droplets, but concluded that, under normal operating conditions, droplets formed from a black liquor nozzle will be stable to aerodynamic forces. High viscosity droplets less than 4mm in diameter will not break into smaller droplets in a recovery boiler.

In a study designed to produce droplets of black liquor with a narrow size distribution, Bousfield (2) designed and operated a prototype nozzle assembly in which both the flow direction and the cross-flow direction momenta were modulated. The nozzle assembly employed two impinging jets, each of which could be adjusted to range from in-phase to 180 degrees out-of-phase. Black liquor (68% solids) flow rates were typically 6 gallons per minute from each jet, yielding jet velocities of 3.0 meters per second. A square root-normal distribution was used to fit the data; a normalized standard deviation (S^*), defined as the standard deviation divided by the square root of the mass-median diameter (D_m), was calculated to measure the spread of the droplet size distribution independent of the droplet size. The two black liquor runs with flow modulation and swirl gave values for D_m of 0.67 and 0.66mm and for S^* of 0.24 and 0.22mm. These values were surprisingly similar to the splashplate nozzle results of Spielbauer et al. (4). No explanation was given; however, data on water alone indicated that lower values of S^* might be obtained with a much broader database where experimental conditions were varied.

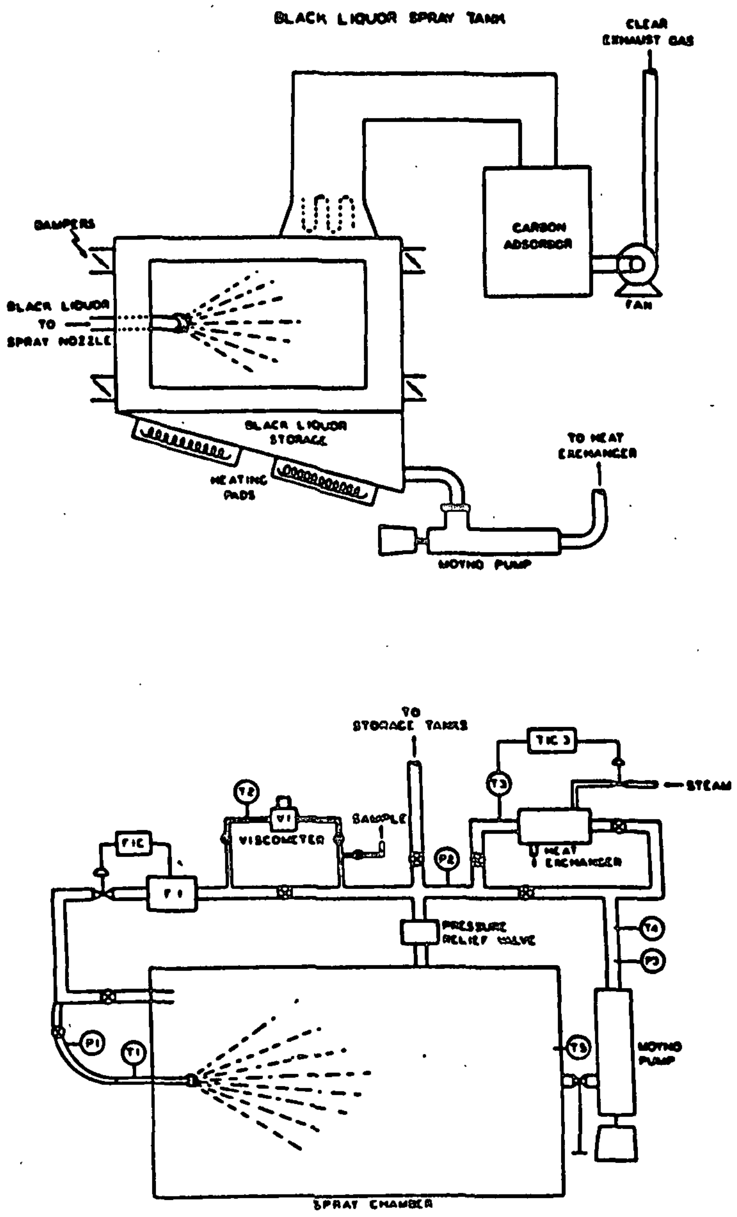
The results from their black liquor runs were difficult to analyze because not all of the liquor existed in the form of droplets. The video images showed the existence of many filaments. The filaments were put into the same size category as a droplet which darkened the same number of pixels. This procedure tended to put filaments in bigger size categories than they should have been, based on the mass of the liquor contained in the filament. Although this gave higher calculated mean droplet sizes, this error should not have influenced the normalized standard deviation.

EXPERIMENTAL

For the present study, black liquors were obtained from several kraft mills and sprayed continuously through commercial black liquor nozzles using a heated recirculating pump-around loop system. The critical component in the system was the spray chamber which served the dual purpose of providing a visible spray pattern while containing and storing the liquor inventory. A two-stage Moyno pump and stainless steel piping allowed black liquor to be pumped from the bottom of the chamber through a heat exchanger and control valves for temperature and flow rate adjustment and then back to the nozzle for spraying again (c.f. Fig. 1). Because of odor control considerations, the spray chamber was operated under a slightly negative draft. An ID fan drew air in through eight adjustable dampers, after which this flow plus any volatiles coming from the liquor spray were pulled through a carbon absorber (provided by Westvaco Corp.) before being exhausted to the atmosphere.

The stainless steel spray chamber was 2.1m long, 1.8m deep, and 3.0m high with a V-shaped heated bottom that could store up to 1100 liters of liquor at 94°C (c.f. Fig. 1). The front and rear walls contained 1.5m x 1.2m tempered glass windows to allow back-lighting and videotaping of the liquor spray sheet and droplets. The side of the chamber had an opening for the spray nozzle which was oriented to deliver the liquor spray sheet in a horizontal direction parallel to the windows. Baffles just beyond the nozzle were used to restrict the spray pattern that was videotaped to a narrow path parallel to the windows and to prevent black liquor droplets from collecting on the windows. A second set of baffles at the end of the chamber opposite the spray nozzle was used to reduce the splash-back of liquor off the wall onto the window. Another set of baffles was attached to the front window around the field-of-view of the video camera to keep that area clean.

Figure 1. IPST Black Liquor Spraying Facility.



Prior to videotaping, black liquor was pumped from the spray chamber through a spiral heat exchanger, which could raise the liquor temperature by 15°C at 190ℓ/min., then through a Brookfield viscometer and back to the chamber. When the liquor was at the desired conditions for testing, the bypass loop was closed and the flow directed through the spray nozzle. Under normal conditions, the system had the capacity to deliver up to 150ℓ/min. at 5.5×10^5 Pa (80 psi) to the nozzle, as measured by a Foxboro magnetic flowmeter. A continuous water addition line was included in the liquor supply system to replace any water vapor which escaped from the hot liquor spray and exited the system with the exhaust air, thereby maintaining a constant liquor solids content.

Continuous estimates of the liquor solids content were obtained through a correlation with liquor temperature and viscosity, which were continuously monitored. The most useful correlation method is to relate the logarithm of the reduced viscosity, defined as the ratio of the liquor viscosity to the viscosity of water at the same temperature, to the temperature divided by percent solids. For black liquor from the Mead Corp. mill in Phenix City, AL, viscosity was correlated by Eq. (2) with an R-squared of 0.95:

$$\mathrm{Log}\left(\frac{\mu}{\mu_w}\right) = [65.62\ T/(S \times T^*) - 0.668]^{-1} \qquad (2)$$

where: μ = liquor viscosity (cP)
μ_w = water viscosity at T (cP)
S = liquor solids content (%)
T = liquor temperature (°K)
T^* = reference temperature (373°K)

An Epson 286 IBM compatible computer was used as the basis of the data acquisition system which recorded temperatures, pressures, flow rate, and viscosity. When videotaping was in progress, the data were collected rapidly so that a good average of the sampled values could be established. The data were stored in an ASC II format file, which were then easily ported to a Lotus 123 file for data analysis.

Images of the black liquor spray were collected with a high-speed video camera developed by Xybion Electronics Systems. The model ISG-250 camera is capable of collecting 30 images per second with an exposure time which can be set from 25 nanoseconds to 20 microseconds per image. The images were recorded with a JVC Super-VHS videotape recorder to maintain the camera resolution of 768 x 493 pixels. The recorder had digital tracking to allow clear analysis of individual frames.

The key to the droplet size analysis was the TN-8502 image analyzer manufactured by Tracor Northern. This system, including the main computer, image monitor, mouse, and printer, was connected to the Super-VHS recorder, allowing images to be acquired by the computer directly from the VCR. The original gray level image was processed to reduce the background to a more uniform gray level and then was converted to a binary image. The binary image was filtered to further enhance the image, after which the computer analyzed the image to determine number and sizes of drops. These data were then transferred to another computer for further statistical analysis.

An assessment of the accuracy of the image analysis techniques was made using ball bearings and cylinders of known diameter. Measurement error was found to be less than 6% for diameters greater than 2mm; the minimum quantitatively measurable (±50%) diameter was about 0.5mm. Measurement of actual black liquor drops may be less precise, since the background is less uniform, and some particles tend to be out of focus.

Spraying at the higher solids levels tended to be problematic; strands and ligaments, rather than droplets, appeared in the field-of-view in the same manner as reported by Bousfield (2). An expanded chamber to extend the field-of-view would be needed to resolve this problem.

RESULTS

A 3^4 test matrix was examined using three liquor nozzles (B&W Splashplate, CE Swirl cone, and SS V-jet), three solids levels (50, 60, and 70%), three viscosities (0.03, 0.09, and 0.27 Pa-s or 30, 90, and 270 cP) and three nozzle pressures (7×10^4, 1.4×10^5, and 2.1×10^5 Pa or 10, 20, and 30 psi). Temperature was adjusted to give the desired viscosity/pressure combinations.

Flow Rate/Pressure Drop Correlations

Flow rate/pressure drop characteristics for the three nozzle types investigated were correlated from a standard mechanical energy balance using the following equation:

$$\Delta P = C_f \left(\frac{1}{2}\rho V_n^2\right) \qquad (3)$$

where:

	ΔP	=	pressure drop (Pa)
	ρ	=	liquor density (kg/m^3)
	V_n	=	nozzle velocity (m/s)
	C_f	=	flow coefficient

The flow coefficient is a function of the type of spray nozzle. For the three splashplate nozzles tested (B&W 12/45, B&W 15/52, and Tampella 18mm), C_f was independent of nozzle diameter and varied with Reynolds Number (70-8,000) according to the following equation ($r^2 = 0.912$):

$$C_f = 1.24 + 458\ Re^{-0.9} \qquad (4)$$

For the SS V-jet nozzle (V-11/65), the correlation was:

$$C_f \quad = \quad 1.09 + 540\ Re^{-1.35} \qquad (5)$$

while for the CE V-jet nozzle (V-15), the correlation was:

$$C_f \quad = \quad 1.26 + 1089\ Re^{-1.35} \qquad (6)$$

For the CE swirl cone (Sw-12), the correlation was not good. The flow coefficient was independent of Reynolds Number and had an average value of 1.11.

Droplet Size Distribution

Several drop size distribution models were applied to the experimental data (Table 1), including Log-Normal, Square Root-Normal, Upper Limit-Log-Normal, and Rosin-Rammler. The best choice was the Square Root-Normal (SQRTN) distribution, shown typically in Fig. 2, where cumulative volume fraction is plotted against the diameter function. This model has only two parameters, the mass- median diameter (D_m) and the standard deviation (S). Interestingly, the data show that the ratio of S to $\sqrt{D_m}$, called the normalized standard deviation (S*), is essentially constant for a given nozzle, thus reducing the SQRTN distribution to a one-parameter model, namely the mass-median diameter. Based on the data in Table 1, the normalized standard deviations for the splashplate, swirl cone, and

Figure 2. Normalized Distribution, R18A.

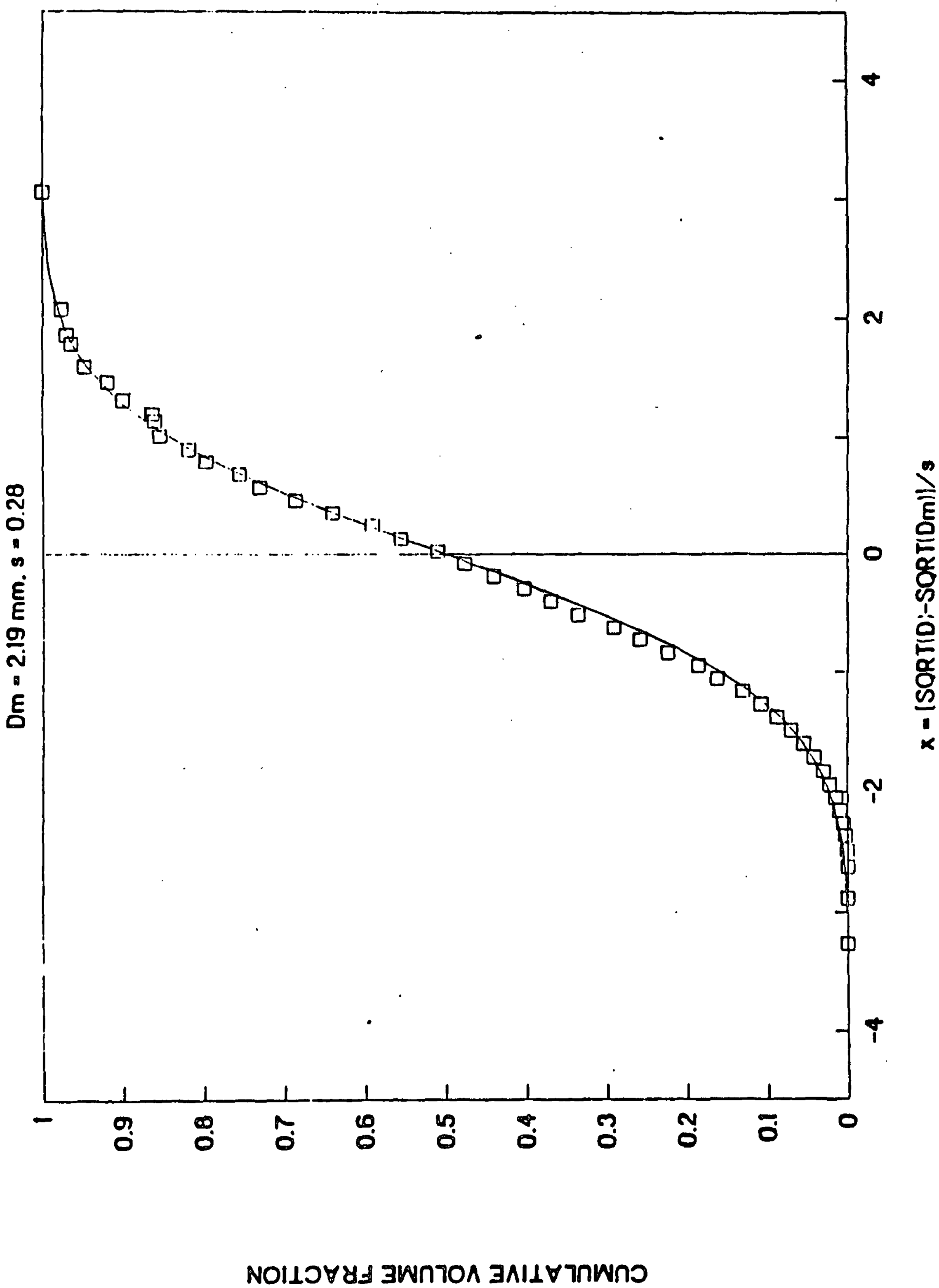


Table 1. Test Conditions and Droplet Size Data Used in Dimensionless Group Correlations.

Test	Solids (%)	Spray Nozzle	Pressure (psi)	Temp. (°C)	D_m (mm)	s ($mm^{1/2}$)	$s/\sqrt{D_m}$
11A	50.2	CE swirl	8.3	32.0	2.67	0.31	0.190
11B	50.2	CE swirl	22.2	33.0	2.20	0.28	0.189
11C	50.2	CE swirl	31.6	33.9	2.16	0.28	0.191
11D	49.0	CE swirl	10.1	33.4	2.34	0.31	0.203
11E	48.9	CE swirl	21.5	34.4	2.22	0.29	0.195
11F	48.9	CE swirl	30.2	35.9	2.03	0.26	0.182
11G	48.5	CE swirl	30.5	53.8	1.95	0.24	0.172
11H	48.5	CE swirl	21.6	52.1	2.12	0.26	0.179
11I	48.3	CE swirl	11.0	51.0	2.38	0.25	0.162
12A	57.4	CE swirl	12.0	56.6	2.70	0.34	0.207
12B	57.3	CE swirl	17.1	56.3	2.37	0.30	0.195
12C	56.7	CE swirl	30.5	55.9	2.00	0.27	0.191
12D	54.9	CE swirl	30.0	68.6	1.85	0.23	0.169
12E	55.3	CE swirl	18.8	68.8	2.07	0.27	0.188
12F	55.7	CE swirl	9.7	72.0	2.11	0.29	0.200
12G	53.4	CE swirl	10.0	92.3	2.25	0.29	0.193
12H	53.4	CE swirl	19.2	92.7	1.93	0.25	0.180
12I	53.9	CE swirl	31.9	93.0	1.82	0.23	0.170
13B	61.9	CE swirl	22.1	74.1	2.14	0.27	0.185
13C	62.0	CE swirl	29.3	75.2	2.00	0.26	0.184
13D	61.7	CE swirl	29.3	91.8	1.66	0.24	0.186
13E	61.9	CE swirl	18.4	95.7	2.04	0.27	0.189
13F	62.3	CE swirl	10.1	99.7	2.18	0.28	0.190
13G	62.1	CE swirl	11.3	124.5	1.07	0.16	0.232
13H	60.6	CE swirl	20.3	120.4	2.00	0.24	0.170
13I	61.8	CE swirl	31.3	120.0	1.87	0.24	0.176

Table 1. (Continued)

Test	Solids (%)	Spray Nozzle	Pressure (psi)	Temp. (°C)	D_m (mm)	s ($mm^{1/2}$)	$s\sqrt{D_m}$
18A	52.1	SS V-jet/65	8.9	36.8	2.19	0.28	0.189
18B	52.3	SS V-jet/65	20.7	36.3	1.95	0.25	0.179
18C	52.5	SS V-jet/65	31.8	35.8	1.86	0.23	0.169
18D	51.0	SS V-jet/65	30.9	53.2	1.72	0.22	0.168
18E	51.1	SS V-jet/65	18.9	53.6	1.90	0.27	0.196
18F	51.4	SS V-jet/65	9.4	53.4	2.23	0.29	0.194
18G	49.6	SS V-jet/65	9.2	68.5	2.08	0.27	0.187
18H	49.9	SS V-jet/65	20.9	70.0	1.73	0.23	0.175
18I	49.5	SS V-jet/65	32.7	74.4	1.68	0.23	0.177
17A	59.4	B&W 12/45	46.6	62.4	2.45	0.38	0.242
17B	59.2	B&W 12/45	31.2	66.2	2.44	0.36	0.230
17H	59.9	B&W 12/45	45.5	88.7	2.27	0.38	0.252
17I	60.5	B&W 12/45	29.4	91.5	2.10	0.32	0.221
17K	57.0	B&W 12/45	15.6	109.9	2.59	0.35	0.217
33D	60.9	B&W 12/45	25.3	103.8	2.36	0.32	0.208
33E	59.5	B&W 12/45	40.0	93.1	2.22	0.29	0.195
36G	56.2	B&W 12/45	19.5	100.6	2.64	0.35	0.215
36H	55.9	B&W 12/45	32.7	100.5	2.05	0.26	0.189

V-jet nozzles are 0.22 ± 0.03, 0.19 ± 0.02, and 0.18 ± 0.02 $mm^{1/2}$, respectively. This is a highly significant result because it implies that all three nozzles gave essentially the same distribution width.

That this can be so may be rationalized through the basic laws of mass and momentum conservation. What is essential is the balance between viscous, inertial, pressure, and surface tension forces present in the system. These are dependent upon fluid properties, flow velocities, and nozzle dimensions, i.e., the fluid mechanics of the system. There are no independently applied forces to change or upset the naturally occurring balance. This would imply that changes in drop size distribution, both in shape and width, must come from a nozzle design that features some independent external force, such as vibratory assist.

Effect of Operating Parameters

It is useful to correlate drop size with the various physical and operating parameters of the system. This is most effectively done by relating the ratio formed from the mass-median diameter and the nozzle diameter to the product of selected dimensionless groups, each raised to some experimentally determined, non-integral power. The dimensionless groups considered were Reynolds, Weber, Euler, Ohnesorge, and Schmidt Numbers, each group being characterized by a ratio of physical forces (Reynolds

No. = inertial forces/viscous forces; Weber No. = inertial/surface tension; Euler No. = vapor pressure/inertial; Ohnesorge No. = viscous/surface tension; and Schmidt No. = momentum transfer/mass transfer rate). Correlations incorporating Weber or Ohnesorge Numbers were not included because of a lack of surface tension data. Physically, Euler No. characterizes the vaporization of water (vapor pressure driven) from the sheet, leading to the formation of perforations; Schmidt No. characterizes the diffusion of water through the liquid sheet to the gas-liquid interface, again leading to perforations.

$$\text{Euler No. (Eu)} = \frac{g_c P_w}{V_n^2 \rho}$$

$$\text{Schmidt No. (Sc)} = \frac{\mu}{\rho D_{WL}}$$

where: P_w = vapor pressure of water

D_{WL} = diffusivity of water in black liquor

Taking two groups at a time proved more effective than three in that the additional arbitrary parameter gave no significant improvement to the goodness of fit. Using the general form:

$$\frac{D_m}{D_n} = k\, Re^a\, Eu^b\, Sc^c \qquad (7)$$

Table 2. Empirical Correlations for the Drop Sizes of Black Liquor Sprays.

TEST SERIES	k	a	b	c	r^2
11	0.6420	-0.1354	0.0943		0.9550
12	0.6837	-0.1774	0.1120		0.8515
13	0.5526	-0.1707	0.1246		0.6686
18	0.7312	-0.1188	0.1121		0.9368
11	0.1041		0.1612	0.0894	0.9609
12	0.0563		0.1946	0.1154	0.8583
13	0.0443		0.2047	0.1153	0.6637
18	0.1426		0.1725	0.0811	0.9372

Table 2 presents values for the arbitrary parameters. There does not appear to be any basic difference between the two correlations shown.

If the dimensionless groups are broken down in terms of their component parameters, the dependence of D_m emerges for the swirl cone nozzle:

$$D_m = \begin{cases} [1.67(D_n)^{0.86}](V)^{-0.32}(\rho)^{-0.23}(\mu_L)^{0.14}(P_w)^{0.09} & \text{(8a)} \\ [0.10(D_n)^{1.00}](V)^{-0.32}(\rho)^{-0.25}(\mu_L)^{0.09}(P_w)^{0.16}(D_{WL})^{-0.09} & \text{(8b)} \end{cases}$$

and for the V-jet:

$$D_m = \begin{cases} [1.68(D_n)^{0.88}](V)^{-0.34}(\rho)^{-0.23}(\mu_L)^{0.12}(P_w)^{0.11} & \text{(9a)} \\ [0.15\,(D_n)^{1.00}](V)^{-0.35}(\rho)^{-0.25}(\mu_L)^{0.08}(P_w)^{0.17}(D_{WL})^{-0.08} & \text{(9b)} \end{cases}$$

where:
- v = nozzle velocity (m/s)
- ρ = density (kg/m^3)
- μ_L = viscosity (kg/m/s)
- P_W = water vapor pressure (Pa)
- D_{WL} = water diffusivity (m^2/s)
- D_m = mass median drop diameter (mm)
- D_n = nozzle diameter (mm)

It is interesting to note the relative insensitivity of D_m to liquor physical properties, with exponents in equations (8) and (9) generally in the 0.1 to 0.3 range. (The apparent stronger dependence on nozzle diameter is artificial, since, in these correlations, nozzle diameter for each nozzle type was not varied.)

The effect of nozzle diameter has been determined independently for the splashplate, as shown in Table 3. Drop size data were obtained for three different nozzle diameters (two manufacturers), using 56% solids liquor at 76-100°C, 0.07-0.215 Pa-s, and velocities of 10-17 m/s.

Table 3. Test Conditions for Splashplate Nozzles.

Test	Nozzle	D_n (mm)	D_m/D_n	Solids (%)	VEL (m/s)	Tl (C)	VISC (kg/m/s)	DENS (kg/m^3)	Pw (Pa)
36A	B&W	9.525	0.3025	55.3	9.95	76.0	0.2150	1310	40187
36B	B&W	9.525	0.2101	55.9	14.73	79.5	0.1960	1303	46400
36G	B&W	9.525	0.2773	56.5	12.03	100.6	0.0713	1296	103680
36H	B&W	9.525	0.2153	57.3	16.28	100.5	0.0706	1296	103293
38A	B&W	9.525	0.2731	54.9	11.35	81.5	0.1247	1296	50202
38B	B&W	9.525	0.2290	55.3	15.50	83.7	0.1256	1297	54901
38C	B&W	11.9	0.2126	55.7	11.31	83.8	0.1341	1300	55035
38D	B&W	11.9	0.2000	55.9	16.27	85.0	0.1396	1301	57838
38E	TAMP	18	0.1756	56.6	12.78	84.9	0.1691	1305	57589
38F	TAMP	18	0.1183	56.5	16.89	85.2	0.1561	1304	58154

Using a modified form of eq. (7),

$$\frac{D_m}{D_n} = K\ Re^a\ Eu^b\ Sc^c\ D_n^d$$

two correlations were obtained:

$$\frac{D_m}{D_n} = \begin{cases} = 4.06(Re)^{-0.16}\ (Eu)^{0.21}\ (D_n)^{-0.61},\ r^2 = 0.836 & (10a) \\ = 0.64(Eu)^{0.28}\ (Sc)^{0.11}\ (D_n)^{-0.81},\ r^2 = 0.836 & (10b) \end{cases}$$

If the dimensionless groups are broken down in terms of their component parameters,

$$D_m = \begin{cases} 12.24(D_n)^{0.23}(V)^{-0.58}(\rho)^{-0.37}(\mu_L)^{0.16}(P_w)^{0.21} & (11a) \\ 0.60(D_n)^{0.19}(V)^{-0.56}(\rho)^{-0.39}(\mu_L)^{0.11}(P_w)^{0.28}(D_{WL})^{-0.11} & (11b) \end{cases}$$

As with the swirl cone and V-jet results above, the liquor physical properties generally have exponents in the 0.1-0.3 range. Mass-median diameter decreases as velocity increases (approx. square root dependence) and increases as nozzle diameter increases.

The effect of temperature on droplet formation from black liquor sprays is important and, of course, does not fall out of equations (8) and (9) because several of the parameters are each temperature dependent. Bennington and Kerekes (3) reported limited results which showed 56% solids black liquor mean drop size to decrease smoothly and slightly over the temperature range of 100- 135°C. (Estimated boiling point was 112°C.) Results from this work are generally in agreement for temperatures below the liquor boiling point. Correlating the data for the swirl cone (Test 11) and the V-jet (Test 18) nozzles as a function of nozzle velocity and liquor temperature only gave the following results:

$$\frac{D_m}{D_n} = \begin{cases} 1.30(V)^{-0.31} \quad (T)^{-0.19} \quad (r^2 = 0.89) & (12a) \\ 0.69(V)^{-0.34} \quad (T)^{-0.09} \quad (r^2 = 0.93) & (12b) \end{cases}$$

where: V = velocity (m/s)

T = temperature (°K)

However, for liquor temperature above the boiling point, droplet formation characteristics changed abruptly, consistent with the observations reported by Galtung and Williams (6). For each nozzle tested, there was a transition temperature (115°C at 60% solids, 130°C at 70%) at which the spray pattern changed from mostly strings and ligaments (80% area basis) to mostly droplets (<30% string area). Mean droplet size decreased by a factor of two (from ~2.8mm to ~1.5mm). This is probably caused by flashing at the nozzle orifice when the temperature exceeds the boiling point of the black liquor. That the previous workers (3) did not report this phenomenon is probably due to the order-of-magnitude smaller droplets (0.2mm) they measured.

Implications for recovery boiler operation are uncertain. For a given nozzle and liquor type and feed rate, control of mean drop size will best be accomplished by controlling the liquor preheat temperature. This abrupt decrease in median drop diameter at the flashing temperature would increase the number of drops being fired into the furnace, increasing in-flight burning rates and probably carryover rates. Exactly what drop sizes a mill will want cannot be answered by this study and will also be boiler specific.

CONCLUSIONS

The black liquor spraying results presented here have added considerably to characterizing nozzle performance. The major conclusions to be drawn are:

1. The droplet size distribution data are correlated well with a square root- normal distribution function. This is consistent with previous black liquor spraying studies and involves only two parameters, the mass-median diameter and the normalized standard deviation. Results from three nozzle types show the normalized standard deviation to be relatively constant at 0.2, rendering the distribution function a one-parameter model.
2. Of the design and operating parameters, the three which most strongly influence mass-median drop diameter are nozzle diameter, liquor density, and velocity. Both density and velocity are related to the kinetic energy of the liquor leaving the nozzle, suggesting that the more energy that is dissipated, the smaller the median drop size. At high solids levels, liquor viscosity becomes important.
3. As liquor temperature passes the boiling point, mean droplet size decreases abruptly by as much as a factor of two, presumably due to flashing at the nozzle. This would result in a several-fold increase in the number of drops being fired into the furnace, increasing burning rates and possibly carryover rates.

4. Present commercial black liquor nozzles do not provide a means for independently controlling droplet size distribution. The fluid dynamics of the spraying system is the main determining force; any significant change will require some externally applied forcing mechanism.

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ACKNOWLEDGMENTS

The authors thank the U.S. Department of Energy for financial support and specifically Stan Sobczynski of DOE for his guiding hand and commitment to the program. Doug Samuels provided skilled and innovative operation of the equipment; contributions of the IPST support staff are also gratefully acknowledged. Finally, we thank the IPST PAC Committee members who provided critical input to the program.